CIRCE: a Dedicated Storage Ring for Far-IR THz Coherent Synchrotron Radiation

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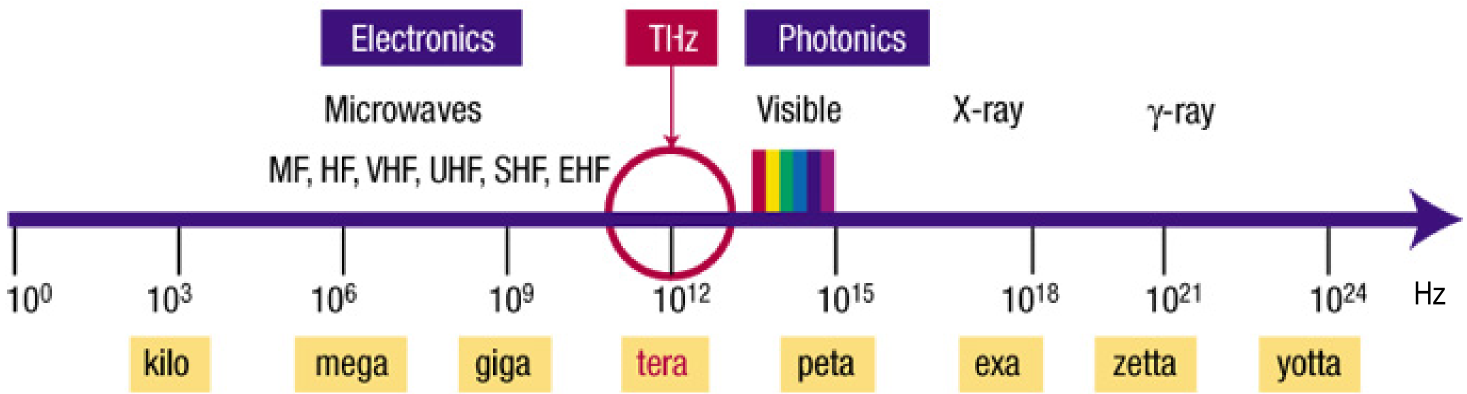
Outline

Why and how to produce Coherent Synchrotron Radiation (CSR) in storage rings

CIRCE: Coherent InfraRed CEnter an optimized CSR source in the THz Far-IR at the ALS

Filling the Terahertz (THz) Gap

"The most scientifically rich, yet underutilized region of the EM spectrum" –Tom Crowe



1 THz
= 4.1 meV
= 33 cm^{-1}
= 300 μm

THz Science: collective excitations, protein motions & dynamics, superconductor gaps, magnetic resonances, terabit wireless, medical imaging, security screening, detecting explosives & bio agents …

"Much brighter terahertz beams are required for scientific and technological applications ... Large average and peak powers could be used to manipulate and alter materials, chemical reactions and biological processes."

-Mark Sherwin, **Nature** *News & Views* **520**, 131 (2002).

It is Time for a New Generation Far-IR (THz) Source

Scientific Workshops convened in
1999, 2000, 2001, 2002

Participants from over 30 institutions

Main Result: A new generation far-IR (THz) source is needed.

Important scientific requirements:
High-stability, High-power, Broadband, Short pulses

***20 Years Basic Energy Sciences Facilities Roadmap* Report Feb 2003:**

- "The BESAC Subcommittee encourages the DOE to organize national workshops to explore the scientific advantages of research with terahertz radiation at user facilities."

DOE, NSF & NIH. Workshop ~ end 2003

A Possible New Generation Source: CSR in Storage Ring

- 1994, First idea of a storage ring based CSR source (1994)

  Murphy & Krinsky, NIM A **346**, 571 (1994).
- Spring 2000, CIRCE Idea Conceived

  Presented at the FIR Workshop at the ALS Users' Meeting, October 2000
- 2002, First demonstration of stable CSR at BESSY

  Abo-Bakr *et al.*, PRL **88**, 254801 (2002)
- 2002, Microbunching instability predicted, simulated and experimentally verified.

  Heifets & Stupakov, PRSTAB **5**, 054402 (2002).
  Venturini & Warnock, PRL **89**, 224805, (2002).
  J. Byrd, et. al. PRL **89**, 224801, (2002).
- 2003, First science with CSR successful

  Singley, *et al., submitted to PRL* (2003).
- 2003, Model for CSR production in storage ring including SR wakefields and microbunching instability.

  Bane, Krinsky, & Murphy, AIP Conf. Proc. **367**, 191 (1996).
  Sannibale, Byrd, *et al.*, *to be published* (2003).

Why a Coherent Synchrotron Radiation Source

In 'conventional' synchrotron radiation (SR) sources the power is proportional to the number of particles in the bunch:

$$P_{SR} \propto N$$

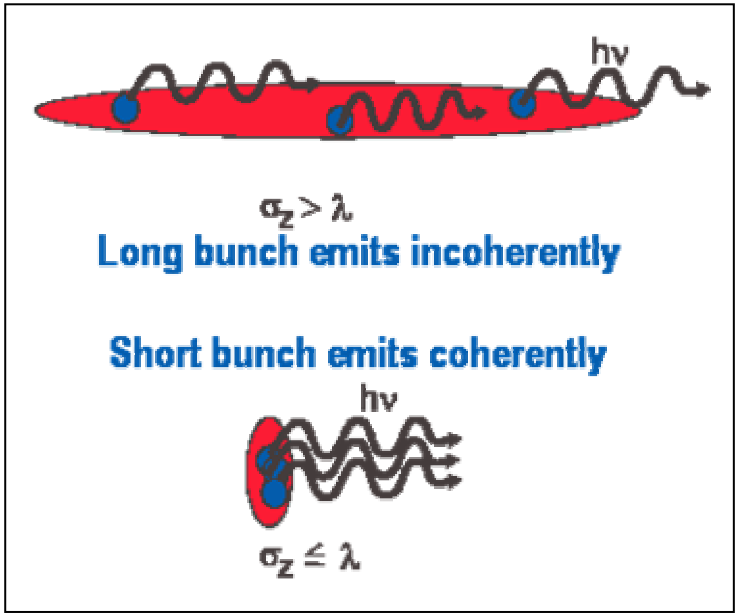
In a coherent synchrotron radiation (CSR) source:

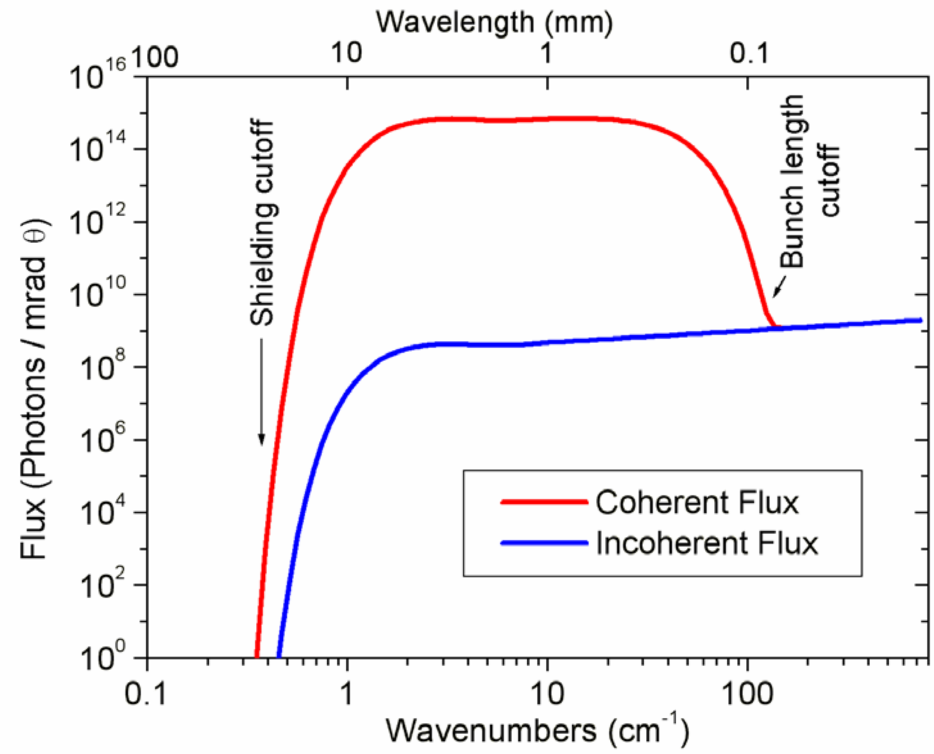
$$\boxed{P_{CSR} \propto N^2}$$

Because N is usually a large number (10^6-10^{10}) the potential gain is huge!

Longitudinal coherence can open to new science possibilities

CSR Basics





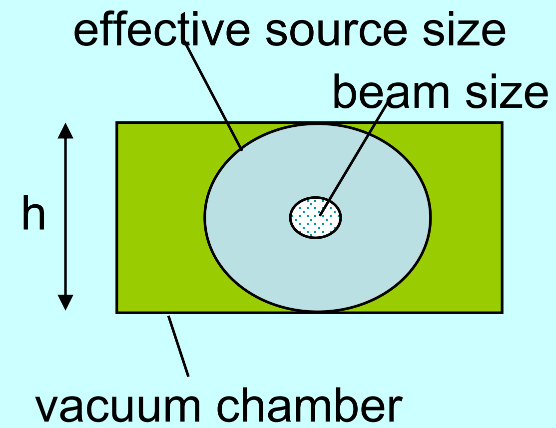
$$\frac{dP}{d\omega} = \frac{dp}{d\omega}\left[N + N(N-1)g(\omega)\right]$$

Nodvick & Saxon, Phys. Rev. **96**, 180 (1954).

Bandwidth Limitations (long wavelengths)

SR Emission is limited at long wavelengths by the vacuum chamber cutoff:

$$\boxed{\lambda < 2\,\frac{h^{3/2}}{\rho^{1/2}}}$$



When the effective size of the SR source is equal to the height of the vacuum chamber, SR is suppressed.

An optimized Far-IR CSR source must have: a cutoff wavelength as long as possible

Short Wavelength Limitation: The CSR Form Factor

$$\frac{dP}{d\omega} = \frac{dp}{d\omega}\left[N + N(N-1)g(\omega)\right]$$

Normalized Bunch Longitudinal Distribution

$$\boxed{g(\omega) = \left| \int_{-\infty}^{\infty} dz\, S(z) e^{i\omega \cos(\theta) z/c} \right|^2}$$

Hirschmugl, Sagurton, & Williams, Phys. Rev. A 44, 1316 (1991).

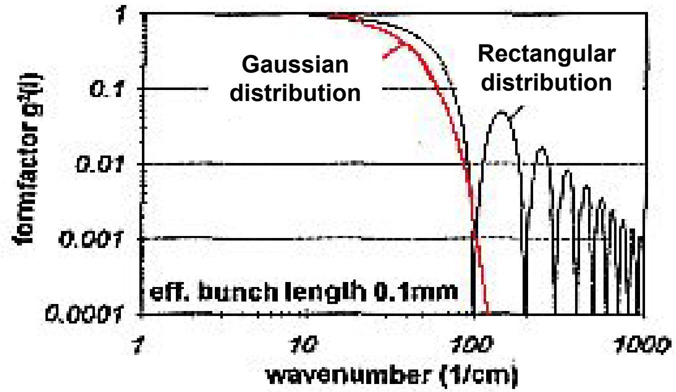


FIGURE 3. Form factor for a Gaussian and rectangular particle distribut

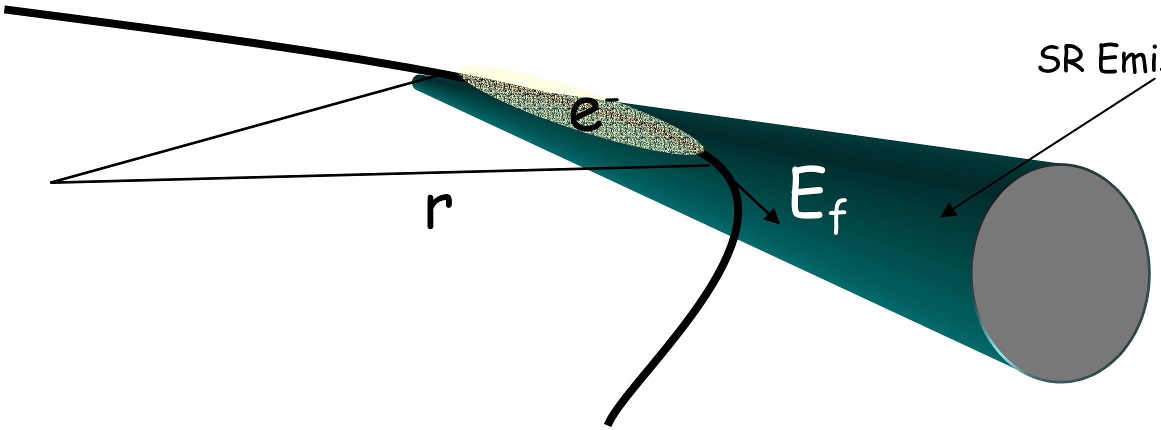
Two possible ways for generating CSR:

Shortening the Bunches: $\sigma_z < \lambda/\pi$ for Gaussian Bunches

and

'Distorting' the Bunches

Short Bunches Regime: The SR Wakefield



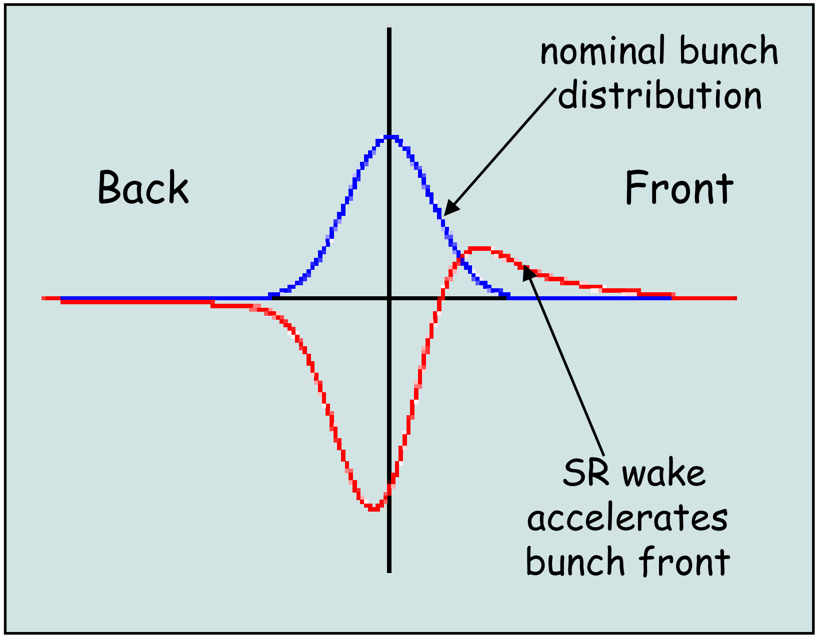
In free space

$$E_\phi = \frac{Z_0 c}{4\pi} \frac{2e}{\left(3^4 \rho^2\right)^{1/3}} \frac{1}{s^{4/3}}$$

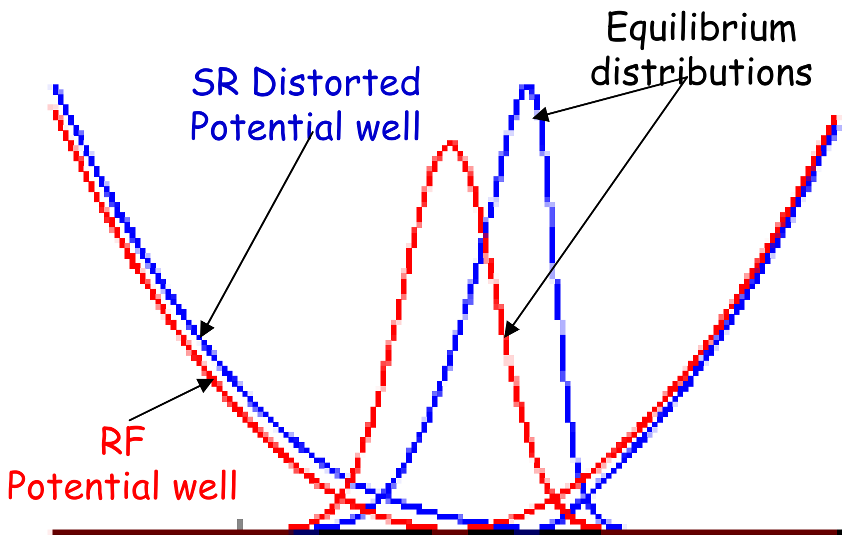
for s>0

Total voltage on a bunch

$$V(s) = 2\pi\rho \int_{-\infty}^{s} ds' E_\phi (s - s') I(s')$$

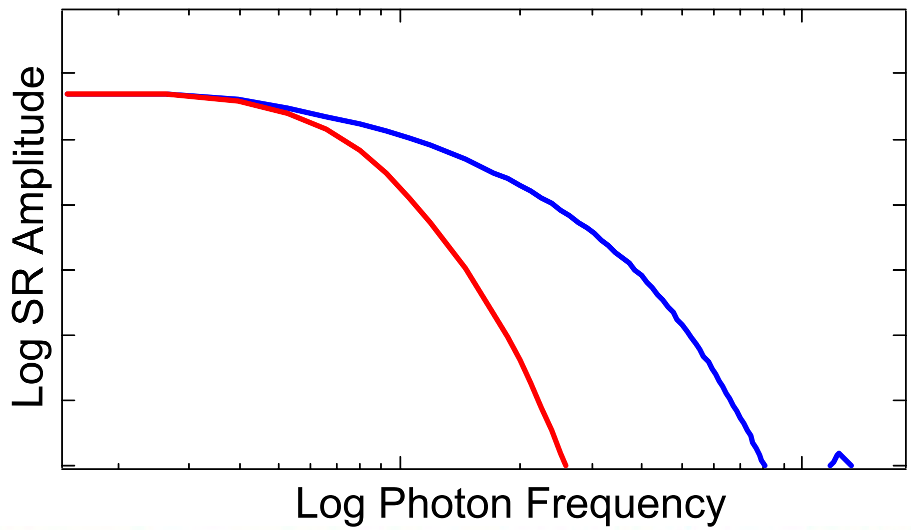


A Qualitative Descriptions



Potential Well Distortion:

From Gaussian bunches to distorted distributions



A Quantitative Description

If the vacuum chamber is properly designed with low cutoff frequency the shielding effects are negligible and:

$$S(s) = \begin{cases} -Z_0 \left(\dfrac{\rho}{3} \right)^{1/3} s^{-1/3} & s > 0 \\ 0 & s \le 0 \end{cases}$$

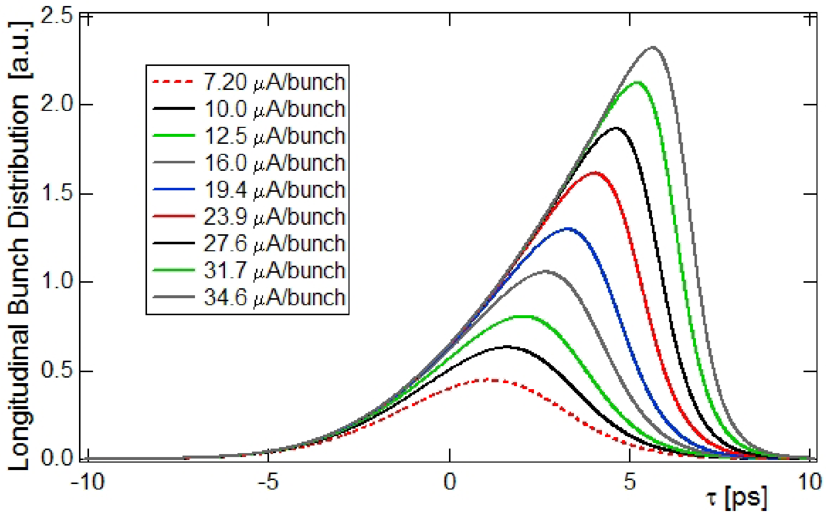
Free Space SR Wakefield (Step Function shape)

$$I(s) = \widetilde{K}\, e^{-\dfrac{s^2}{2\sigma_0^2} - \dfrac{1}{\sigma_0^2 V'_{RF}} \int_0^\infty I(s-s') S(s') ds'}$$

Haissinski Equation

K. Bane, S. Krinsky, J.B. Murphy, *Microbunches Workshop,* Upton NY 1995

Calculated Distributions



Leading edges much sharper than trailing ones.

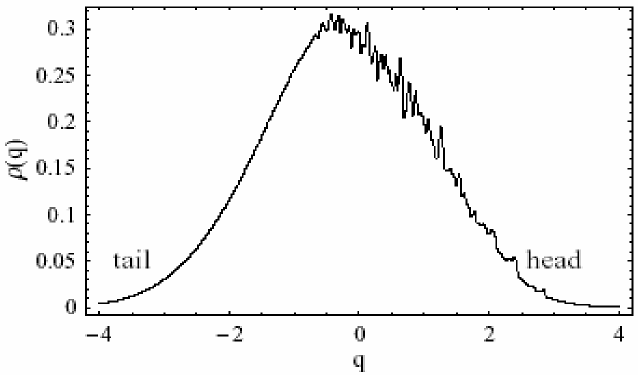
Increasing the current per bunch increases the asymmetry

extending the CSR towards high frequencies!

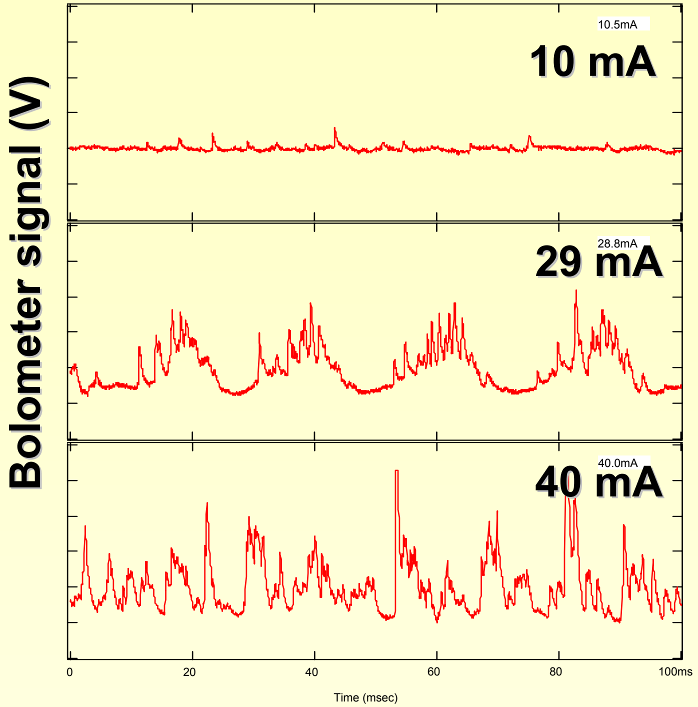
But a limit to the maximum current per bunch exists.

CSR Driven Instability

Above a current/bunch threshold CSR can drive a microbunching instability in the electron bunch generating bursts of terahertz CSR and resulting in a noisy source.



Simulated instability showing bunch shape.
Venturini, WarnocK SLAC



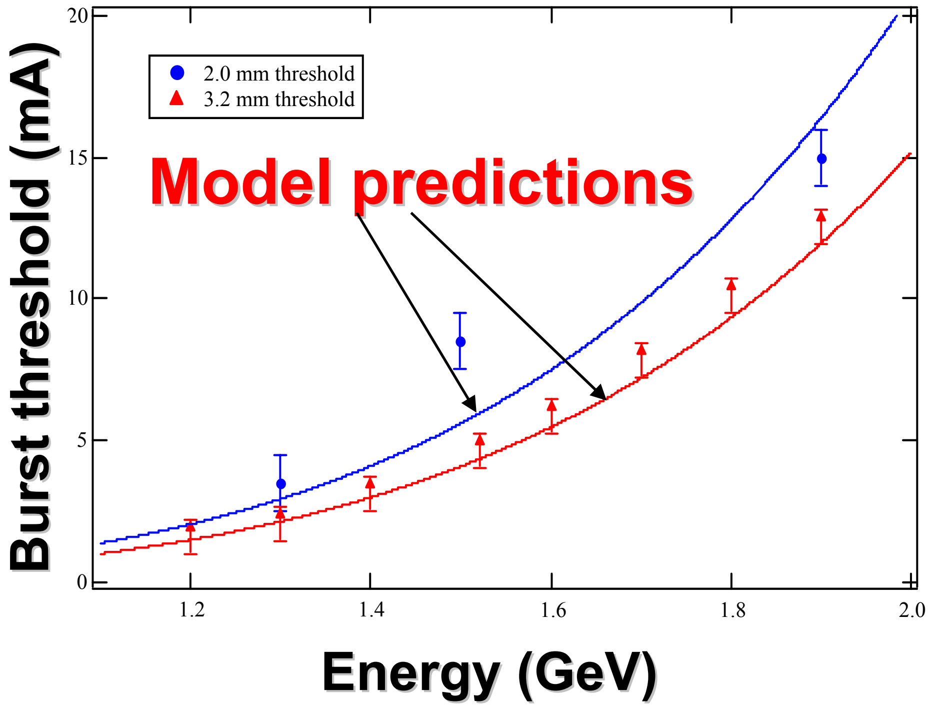
Bursts of far-IR CSR observed on a bolometer at the ALS. Thresholds depends on beam energy, bunch length, energy spread, and wavelength.

S. Heifets, G.Stupakov, PR STAC 5, 054402, 2002.

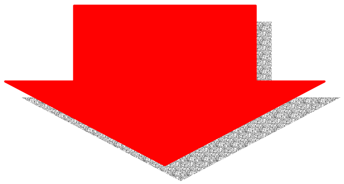
M. Venturini, R. Warnock, PRL 89, 224802, Nov 2002.

CSR Instability Experimental Verification

ALS studies showed first experimental confirmation of the Heifets-Stupakov Model for the microbunching (CSR) instability



Instability thresholds understood:
- agreement w/observations also at other storage rings



Heifets-Stupakov instability model allows the design of a <u>stable</u> Ring Based CSR Source

J. Byrd, et. al. PRL 89, 224801, Nov 2002.

Optimizing a CSR Source

$$\frac{dP}{d\lambda} = C\ N_b \frac{B^{1/3} f_{RF}^2 V_{RF}^2}{L\ E^{1/3}} \frac{\sigma_z^{14/3}}{\lambda^{7/3}} F^2 g(\lambda)$$

C = 2.642 10^{-21} [MKS units]

The factor F is given by the model.
F indicates the bunch distortion: the larger the more distorted is the bunch.

F is limited by the microbunching instability:

$$F \le F_{MAX} \approx 5$$

Define the CSR spectrum by the proper choice of F and σ_z.

For given F and σ_z:

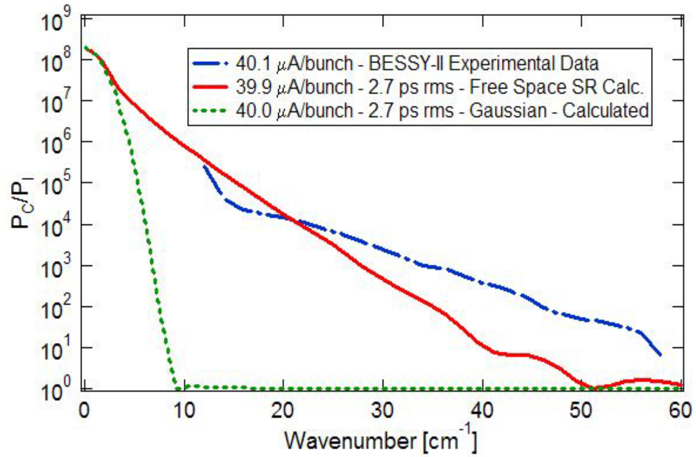
Maximize N_b, B, V_{RF} and f_{RF}

Minimize E and L

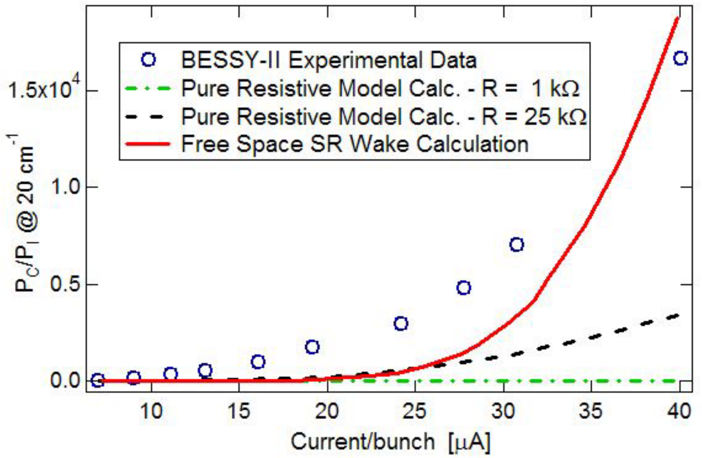
The momentum compaction is used for maintaining σ_z constant while changing the other quantities

Simulation of the BESSY-II Results

Calculations using the model are in good agreement with the published BESSY-II experimental results.

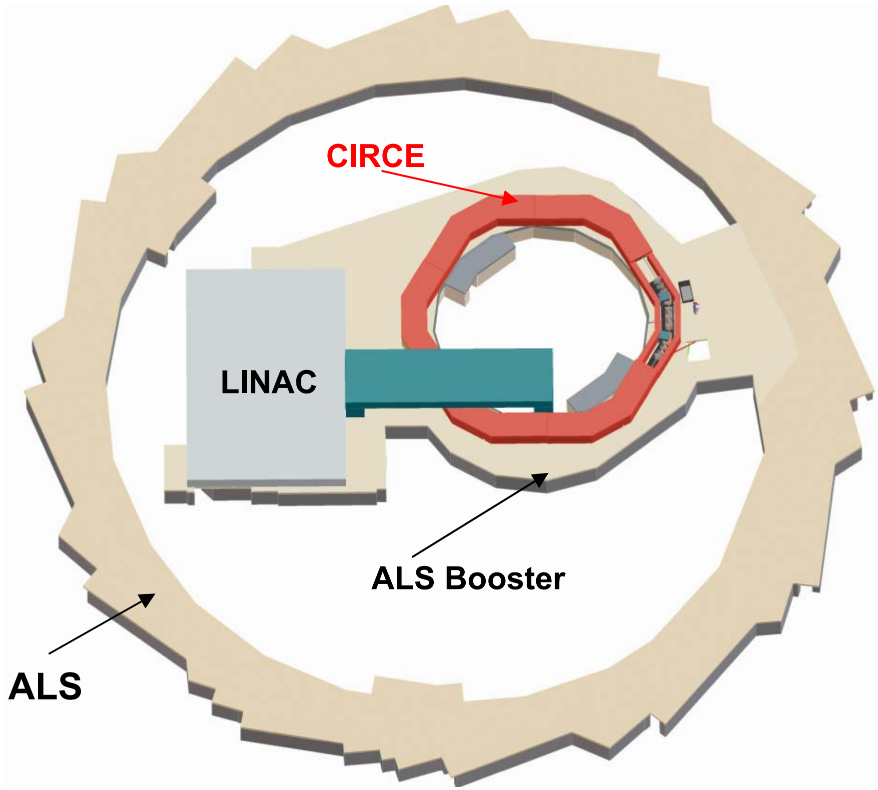


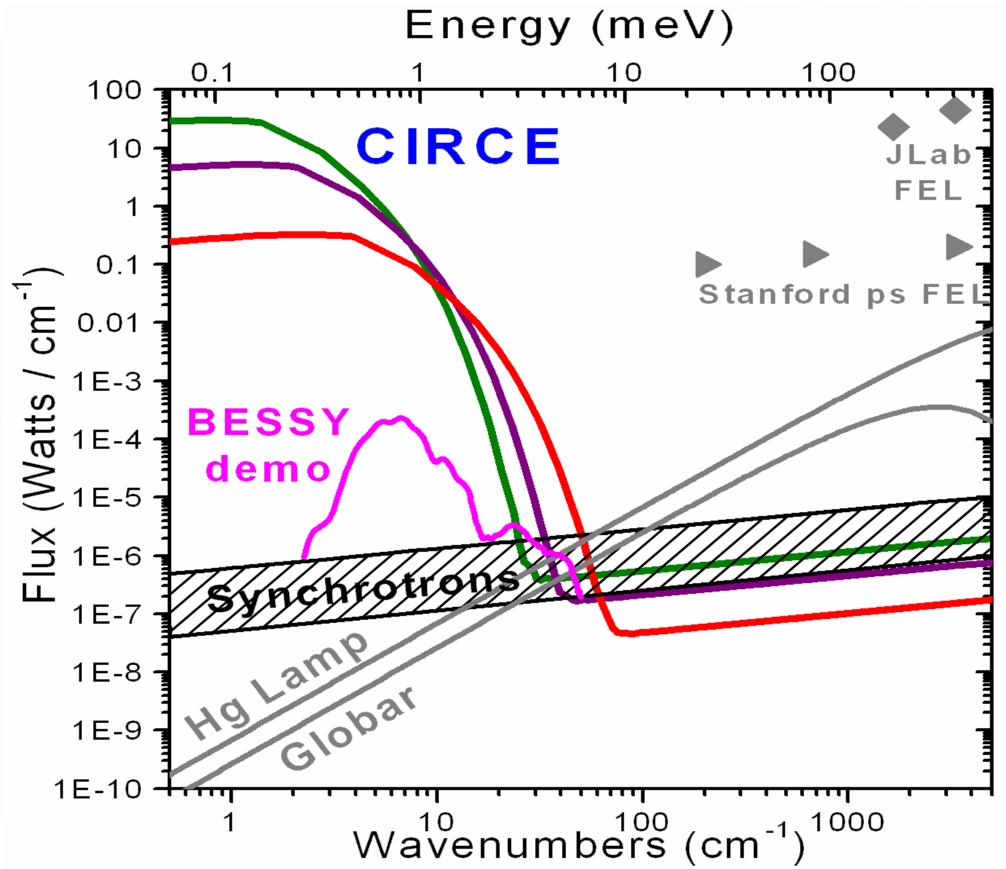
Collaboration with BESSY Group for refining the model (including vacuum chamber shielding, minimize the experimental error, ...)



- M. Abo-Bakr et al., Phys. Rev. Lett. **88**, 254801 (2002)
- M. Abo-Bakr et al., Phys. Rev. Lett. **90**, 094801 (2003)

An Optimized THz FIR CSR Source: CIRCE



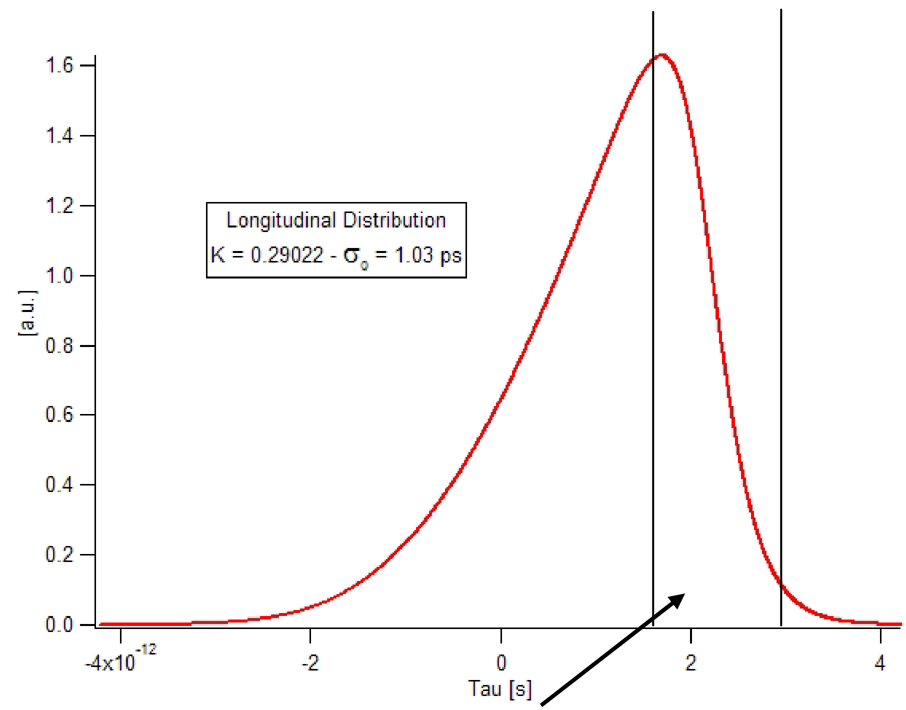


10^6 - 10^8 power gain with respect to existing THz Sources!

CSR Pulse Duration

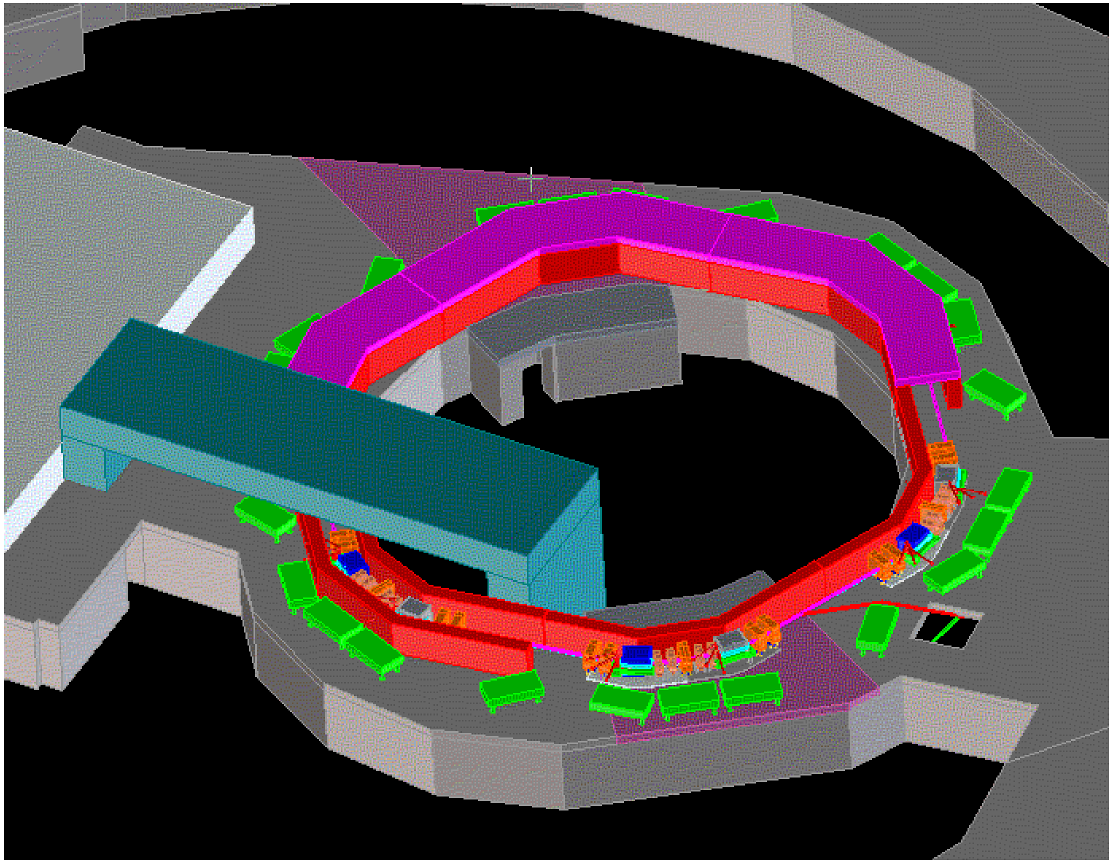
In CIRCE the FIR CSR pulse length is transform limited:

it starts from ~ 300 fs for the shorter wavelengths and gradually increases towards the electron bunch length (1 ps) for the longer wavelengths



High Frequency CSR Emission Region

CIRCE General Features



-Adequate floor space for IR beamline experiments.

-Stable surface supporting ring and beamline.

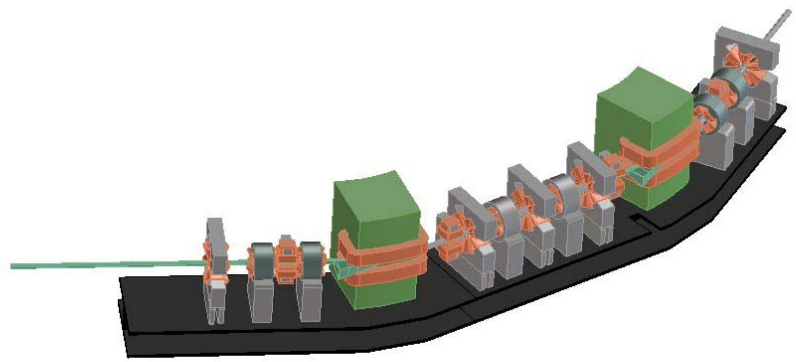
-"Free" full energy (600 MeV) injector-Compatible with ALS topoff operation.

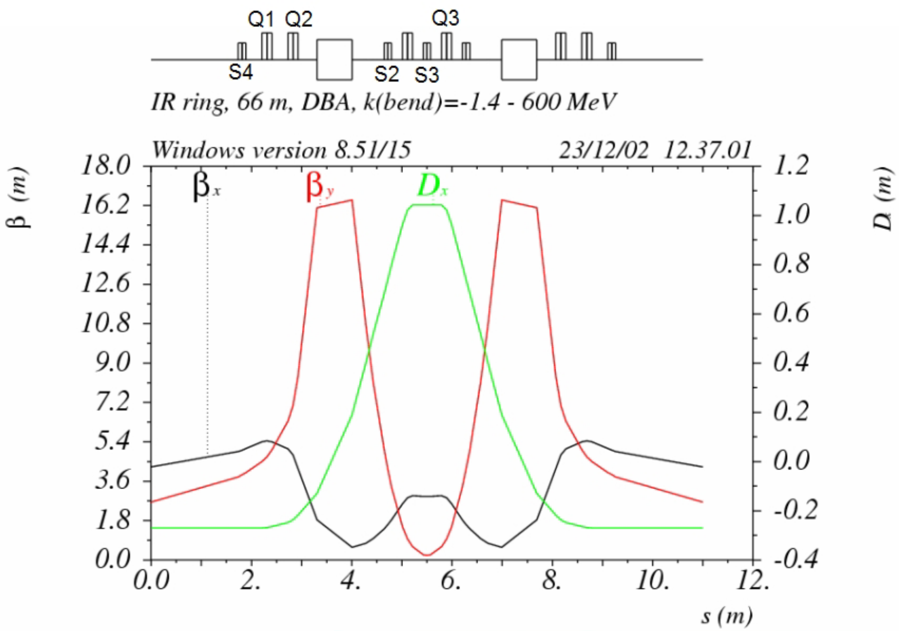
Beam Line Experiments Located on Top of the Booster Shielding

CIRCE Main Characteristics

<u>CIRCE Parameters</u>

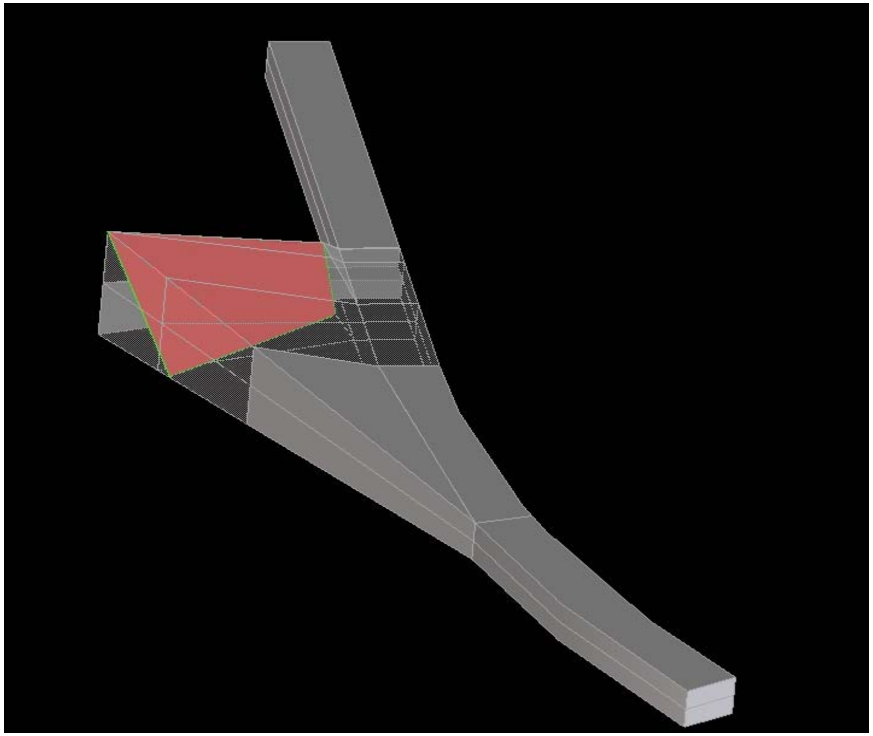
E=600 MeV	f_{rf}=1.5 GHz
V_{rf}=0.6 MV	U_0=8.62 kV
I_{total}=8-90 mA	I_{bunch}=24-270 μA
L=66 m	h=330
σ_τ=1-3 psec	σ_δ=4.5E-4
α=2E-3 - 2E-4	ρ = 1.335 m





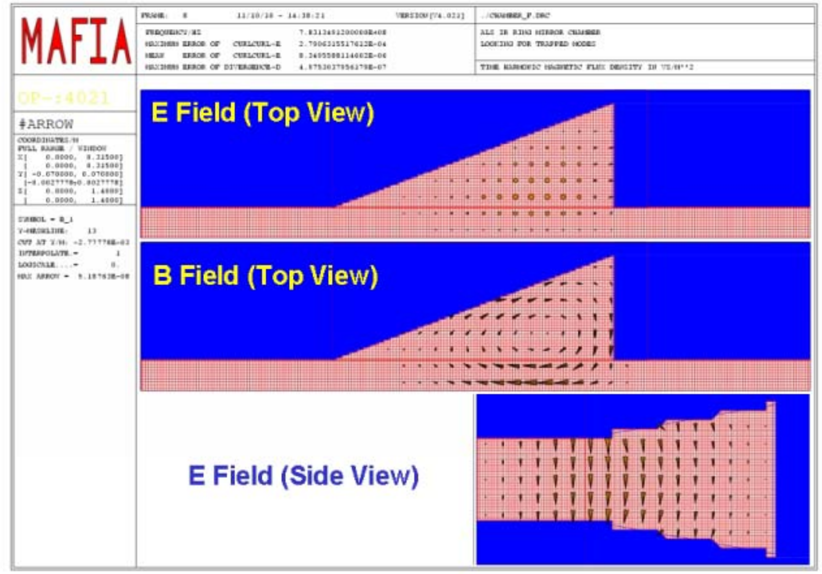
- Periodicity = 6
- DBA lattice 50 nm emittance (diffraction limited in far-infrared)
- variable momentum compaction with up to 3rd order correction
- magnets pre-aligned on girders
- shielding fits directly over magnets (i.e. no tunnel access)

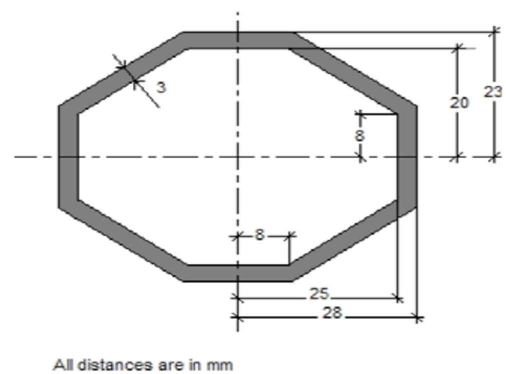
CIRCE
Dipole Vacuum Chamber



Large Vertical acceptance dipole chamber for long wavelengths
300 x 140 mrad^2 H/V acceptance
(95% acceptance @ λ = 1 mm)

Trapped Mode Example



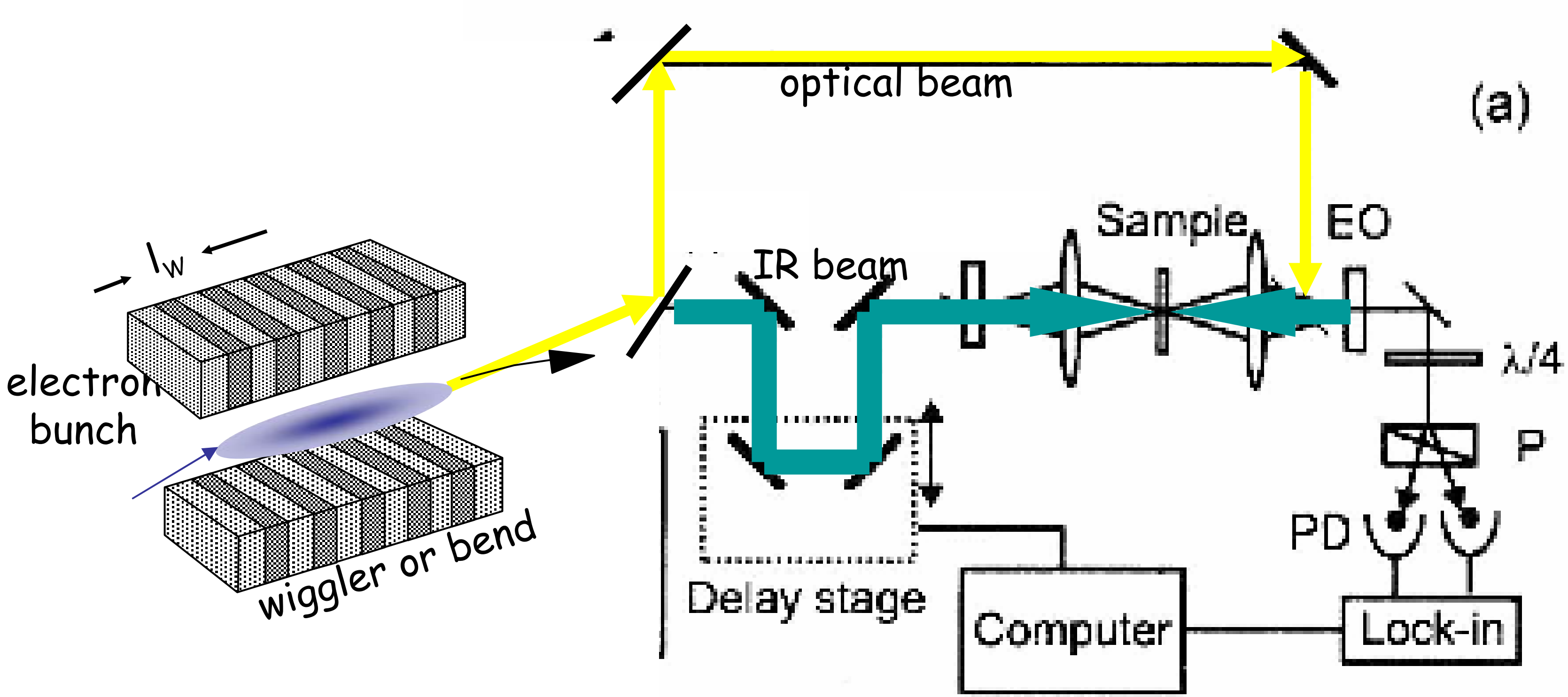


Vacuum Chamber Cutoff ~ 1.4 cm

Novel Techniques for Using CSR

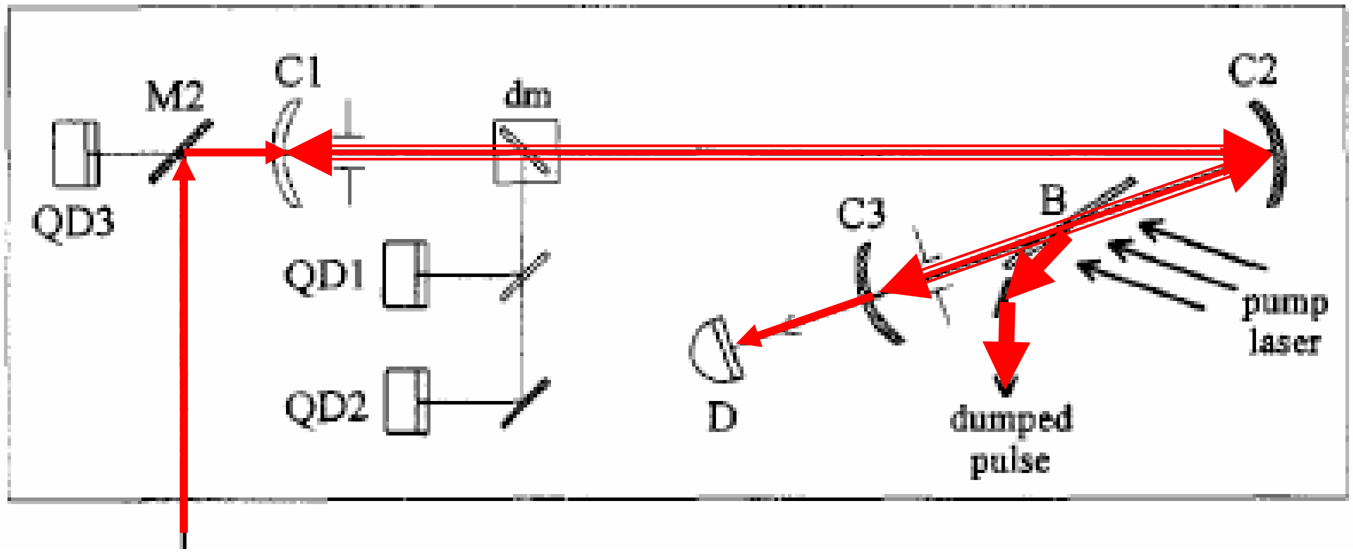
Self-synchronized Electro-optic sampling

- provides functionality of benchtop setup w/1.5 GHz rep-rate
- use inherent synchronization of optical and THz beams
- optical source can be dipole (very weak) or undulator
- self-mixing techniques also possible.



Pulse Stacking

Because input pulses are coherent, it is possible to resonate the signals to gain high pulse power levels.



Input CSR pulses

Peak power limited by cavity Q and phase stability of pulses

T. Smith, et al., NIMA 393 (1997) 245-251.

In Summary

CIRCE Key Properties:

Broadband
High power
High stability
Short pulses (~300 fs)
Flexible to 'fancy' upgrades
Multi-beamline capability

- CIRCE Ring preliminary conceptual design completed:
  - ring lattice, injection, RF system, magnets
  - preliminary engineering design of supports, shielding, ...
  - evaluation of the possible ALS facility upgrades

No technical showstopper.

Cost estimate (LBNL and external companies) (< 20 M$)

We are ready to build!